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MEASUREMENTS OF HEAT TRANSFER RATES BEHIND AXIALLY SYMMETRIC BACKWARD FACING STEPS IN THE SHOCK TUBE

BY

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ABSTRACT

Heat transfer rates were measured in the separated flow region behind a series of eight axisymmetric backward facing step models. Four step heights, 0.85mm, 1.90mm, 2.90mm and 4.00mm were used with two forebody lengths for each of the step heights. The work was performed in the straight section of the shock tube at flow Mach numbers between 1.4 to 2.5, Reynolds number per centimeter of 8×10^3 to 2×10^5 and stagnation to wall enthalpy ratios of 10 to 30. Measured heat transfer rates, which are presented for each of the eight models, indicate low heat transfer rates in the separated flow region and values up to four times the flat plate heat transfer rate in the reattachment zone. Movement of the reattachment zone with flow conditions and model dimensions is also examined and the results are shown to agree with a referenced inverse relation between the value of the peak heat transfer rate and the distance between the separation point to the position of the maximum heat transfer rate.

NOMECLATURE

Δx	distance from separation point (mm)
h	step height (mm)
L	effective forebody length (mm)
Re_L	Reynolds number based on effective forebody length
M_s	incident shock Mach number
M_f	flow Mach number
q	heat transfer rate
$q_{f.p.}$	flat plate heat transfer rate

LIST OF FIGURES

I. INTRODUCTION

It is known that in a separated flow region the heat transfer rates to a surface are "much lower" than those found under similar attached flow conditions in the "dead water" region, but in the reattachment region the heat transfer rates may be many times higher than those found under the corresponding attached flow conditions (Ref. 1 - 5). Furthermore, the average heat transfer rate to the surface, may be higher or lower than that for the equivalent attached flow case, depending upon the "thermal severity" of the reattachment (Ref. 6).

The present work examines the heat transfer rates found in the "dead water" and reattachment regions of separated flows obtained on a series of axisymmetrical backward facing step models. In this manner, the effects of various flow conditions and geometrical variations on the heat transfer rates may be studied and some knowledge of the maximum heat transfer rate and location in the reattachment region may be gained. The objective of this study being to relate the physical test conditions, i.e., model dimensions and flow parameters, to the resulting heat transfer rate data. This work is being performed as a continuation of the separated flow studies which have been underway for the past several years at the Aerodynamic Laboratory of the Technion's Aeronautical Engineering Department. Some of the previous work has been presented in References 6 - 10.

The present investigation was carried out in the shock tube at flow Mach numbers from approximately 1.4 to 2.5, Reynolds numbers per centimeter of 8×10^3 to 2×10^5 and stagnation to wall enthalpy ratios of 10 to 30. The heat transfer rates were measured by the use of thin film platinum resistance thermometers (Ref. 11).

II. EXPERIMENTAL APPARATUS.

Shock Tube and Instrumentation

The experiments described herein were performed in the 3" x 3" shock tube of the Aerodynamics Laboratory of the Technion's Department of Aeronautical Engineering. The shock tube has a 3 inch diameter, 2 meters long high pressure section and a 7 meters long, 3" x 3" square low pressure section. This tube is also used to operate a 10" x 12" shock tunnel nozzle During testing, the low pressure section is evacuated to the pressure level required by test conditions (minimum pressure is approximately 0.7mm Hg. absolute), the test gas is air in all cases. The driver gas is then introduced into the high pressure section from high pressure bottled hydrogen or air. The driver gas pressure is controlled by a copper diaphragm which is scribed to a predetermined depth depending upon the required pressure. The scribing also provides a relatively "clean" break in the copper diaphragm Further details of the shock tube operation are described in References 6 to 10

The local heat transfer rates were measured by thin platinum film resistance thermometers sputtered on pyrex glass which are described in detail in Ref. 11

Models

A series of 8 models was used in the study described herein. The models' configuration and dimensions are given in Fig. 1. Construction of the model is such that the model forebody (the cone-cylinder) are interchangeable. In this way, the instrumented cylindrical part on which the platinum films are located is used for all the experiments and only the cone cylinder forebody is changed to obtain various step heights and model lengths. Table 1 presents the gauge positions behind the steps. The pertinent dimensions for each model are included in Fig. 1.

The models used in this investigation had four step heights, 0.85mm, 1.90mm, 2.90mm and 4.00mm and two cylindrical forebody lengths, 10.0mm and 25.0mm. The effective forebody length, L, for each of the 8 models is presented in Table 2.

III. RESULTS

Presented in Figs. 2 to 9 are the local heat transfer rates related to flat plate values, which were measured at each gage position (distance behind the separation point) for each of the 8 axisymmetric models. In these figures the heat transfer data is plotted against the non-dimensional distance from the separation point $\Delta x/h$, for several values of the parameter $h/L\ Re_L^{1/2}$. The corresponding values of the parameters $h/L\ Re_L^{1/2}$, Re_L, M_s and M_f for each experiment are presented in the table accompanying each figure. As found in previous investigations, the heat transfer results indicate initially low values of the heat transfer rates in the "dead water" region immediately behind the separation point and a subsequent rise and levelling off in the reattachment region. In addition, the heat transfer rates increase with increasing values of $h/L\ Re_L^{1/2}$ in both the "dead water"

region and the reattachment region. It is observed that the reattachment region, indicated here as the position of the maximum heat transfer rate, moves closer to the separation point as the step height is increased, the distance being measured in step heights, $\Delta x/h$. It is also found that the reattachment region moves downstream with increasing forebody length. Movement of the reattachment region is also apparent as a result of variation in the correlating parameter $h/L\ Re_L^{1/2}$, i.e. reattachment moves upstream with increasing $h/L\ Re_L^{1/2}$ for a given model.

In figures 10 and 11 the local heat transfer rates related to the flat plate values which were measured on Models 1 and 3 are plotted as a function of Re_L at various gauge positions. These figures are representative of the results obtained for all the other models. It is clearly seen that low heat transfer rates are measured by gauges in the "dead water" region and higher rates are measured in the reattachment region. Of further interest is the rate of variation of the heat transfer rates as a function of Re_L at each gauge. For gauges in the "dead water" region the heat transfer rate rises rapidly at the higher values of Re_L and slowly at the lower Reynolds numbers, beyond the reattachment region the opposite variation is observed. This results in a "concave" variation in the "dead water" zone and "convex" variation in the reattachment zone. This change of the shape of the curve is well illustrated in Figs. 11 where it is seen that the curve for gauge 3 at $\Delta x/h = 1.53$ is about linear so that it marks the position between the gauges which are in the "unattached" and those that are in the "reattached" flows. It should be mentioned that this is not the point at which the maximum heat transfer rate occurs but

it does indicate a region in which the character of the heat transfer changes.

From the preceding data it may now be possible to investigate the effects of local model dimensions and flow conditions on the heat transfer. Of prime importance is the value and location of the maximum heat transfer rate (occuring in the reattachment region) for a given model. The effect of step height on the maximum heat transfer rate for several values of Re_L is examined in Fig. 12. The maximum heat transfer rate is seen to increase with increasing Reynolds number and step height. This trend is again noted in Fig. 13 wherein the maximum heat transfer rates are plotted against the ratio h/L. It should be noted that in neither Fig. 12 or in Fig. 13 can the data from the shorter forebody models (1, 2, 3, and 4) be joined with the data from the longer forebody models (5, 6, 7 and 8). In Fig. 14 a similar plot is made using the parameter $h/L\ Re_L^{1/2}$ instead of Re_L. Here again the value of the maximum heat transfer rate increases with increasing $h/L\ Re_L^{1/2}$, however it decreases with increasing h/L. The effects of the individual model dimensions are difficult to separate due to the change in forebody length, L, from model to model. This result is, however, consistent with the previous ones since the effects of h/L on the parameter $h/L\ Re_L^{1/2}$ must also be taken into account As shown in Fig. 13, at a constant value of Re_L the experimental data indicates that decreasing maximum heat transfer rates are obtained as the step height is decreased. This trend is also noted in Fig. 14, however, in this case variation of the step height, h, also affects the values of the parameter $h/L\ Re_L^{1/2}$.

In an attempt to show the influence of these parameters, lines of decreasing h are indicated in Fig. 14 (for models 1, 2, 3 and 4 only) for constant values of $Re_L^{1/2}/L$. It should be noted here that at a given value of $Re_L^{1/2}/L$, several lines of varying h may be obtained, e.g. the $Re_L^{1/2}/L = 10.0$ for models 3 and 4. In this case the values of $Re_L^{1/2}$ is 276 for model 4 and is 254 for model 3 and therefore, as expected at the higher Reynolds number value, a higher value of $(q/q_{f.p.})_{max}$ is found.

It is worthwhile now to compare the results obtained in the present work with previously obtained correlations Reference 6 suggests a correlation of the maximum heat transfer rates by the use of the relation

$$q_{max}/q_{f.p} = 0.068\ h/L\ Re_L^{1/2}.$$

Comparison of the present data with this relation is shown in Fig. 15. The results of the present study indicate a somewhat different variation from that of the above equation Based on the $h/L\ Re_L^{1/2}$ correlating factor, a variation of $(q/q_{f.p.})_{max}$ with step height and forebody length is observed indicating that, in addition to the need for a different form of correlation, a configuration sensitive correlation is required

In Fig. 16, the parameter $h/L\ Re_L^{1/2}$ was replaced by Re_L so that now all the measured points appear in approximately the same flow parameter range (Re_L) Here the step height effect on $(q/q_{f.p.})_{max}$ is again evident, namely, increasing heat transfer rates with increasing step heights, and in addition the effect of L may also be seen The peak in $(q/q_{f.p.})_{max}$ appears at approximately the same value of Re_L for the different step heights at a given forebody length L. While,

as noted before, the maximum heat transfer rate is higher for the longer forebody models.

In a previous investigation (Ref. 12) a correlation was found which relates the maximum heat transfer rate at reattachment with the position of this maximum, independent of the model geometry. This correlation is of the form

$$\frac{q_{max}}{q_{f.p.}} = 12 \left(\frac{\Delta x}{h}\right)^{-1}_{max}$$

where $\left(\frac{\Delta x}{h}\right)_{max}$ is the point at which q_{max} first occurs, and was obtained by compilation of the results of a large number of measurements of heat transfer rates in the reattachment zone found in various types of model and flow conditions. Data points from the present study are compared with this correlation in Fig. 17. The present experimental results seem to be in good agreement with this correlation

IV CONCLUSIONS

Based upon the experimental results obtained in this investigation, several general points are quite evident with respect to axisymmetric backward facing step separated flow: (1) Maximum heat transfer rates increase with increasing step height and with increasing forebody lengths; (2) movement of the point of $(q/q_{f.p.})_{max}$ is influenced by step height and by forebody length, (when measured by the dimensionless distance from the separation point, $\Delta x/h$, this point moves upstream with increasing step height and downstream with increasing forebody length); and (3) as shown in Figure 3, the variation of the heat transfer rate with Reynolds number is different in the separated

flow and flow reattachment regions (concave to convex variation) indicating a possible means of defining the thermal reattachment region rather than taking the point of $(q/q_{f.p.})_{max}$ as the "point" of reattachment.

The experimental results obtained for the short forebody models (1, 2, 3 and 4) cannot be correlated with the results for the long forebody models (5, 6, 7 and 8) as was shown in Figures 12 to 14. This naturally leads to the conclusion that there is a need for the formulation of a new similarity correlation to relate the heat transfer in axisymmetric separated flows. It is found that the presently used parameter of $h/L\ Re_L^{1/2}$ does not correlate the results of different model geometries, therefore the new correlating factor must include both flow parameters and model dimensions.

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TABLE 1

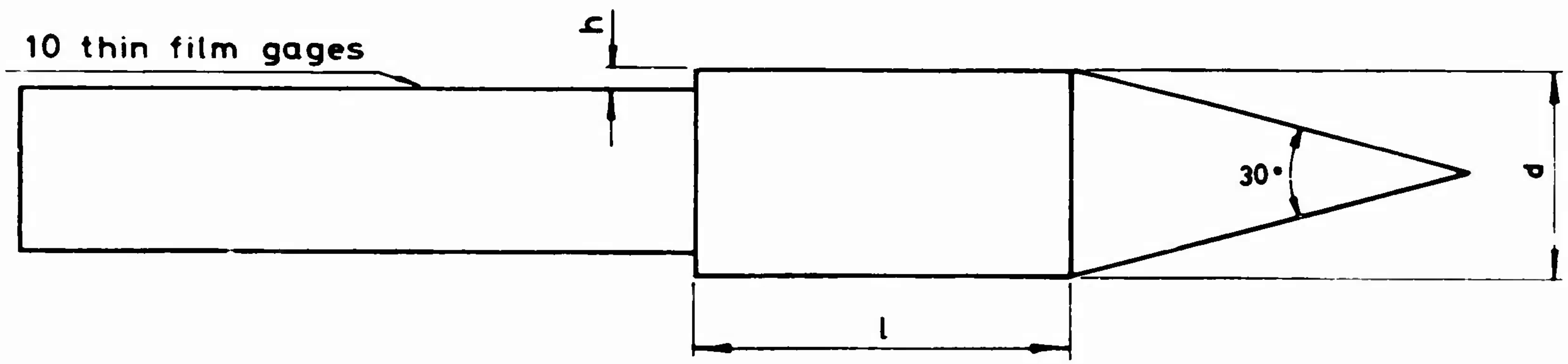
GAUGE POSITIONS ON THE MODEL

Gauge No.	1	2	3	4	5	6	7	8	9	10
Dist. from step (mm)	0.69	2.49	4.45	6.36	8.32	10.10	11.97	14.02	16.06	18.03

TABLE 2

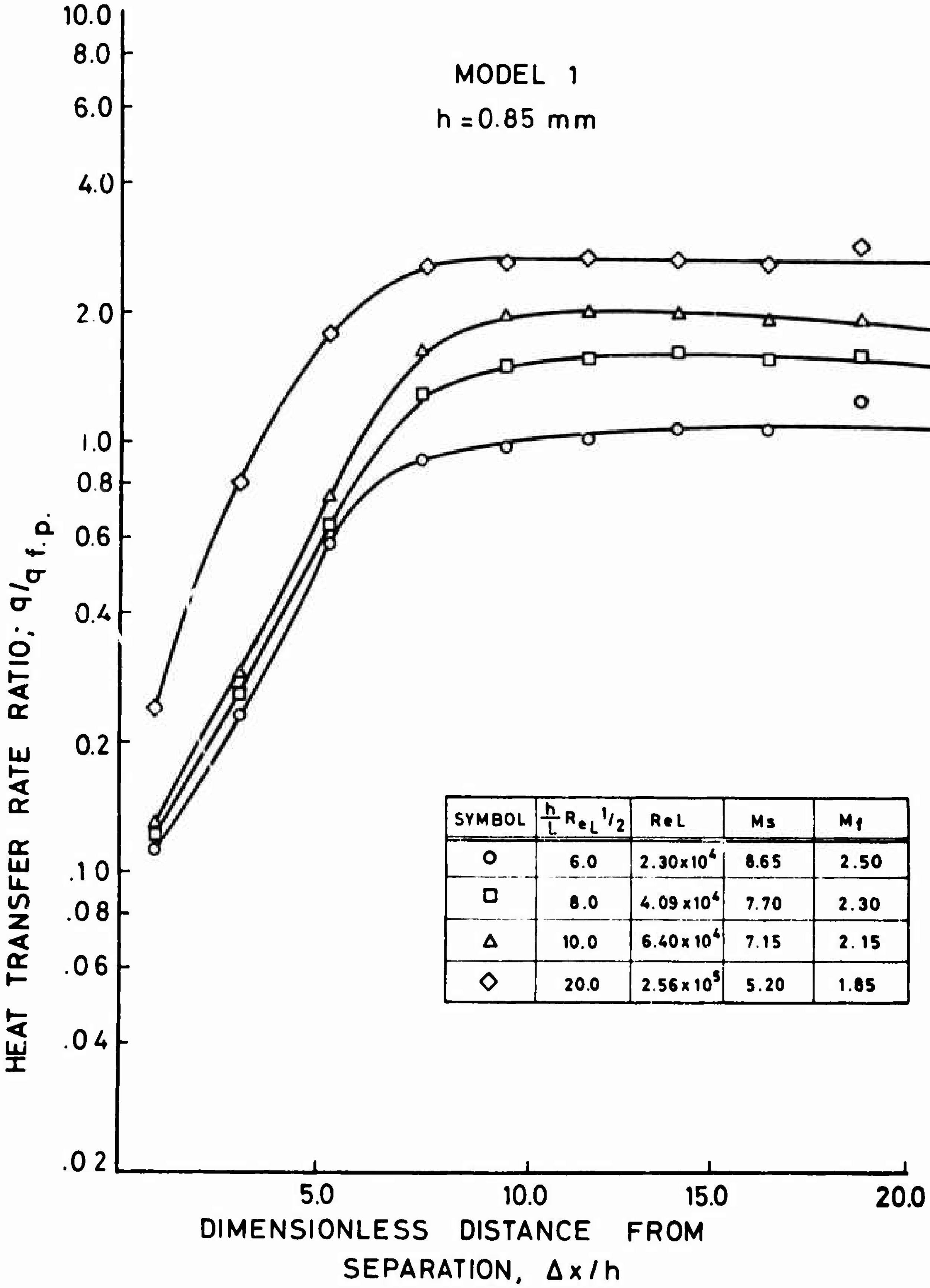
EFFECTIVE CONE-CYLINDER FOREBODY LENGTH FOR THE VARIOUS MODELS

Model	1	2	3	4	5	6	7	8
Effective Forebody Length L (mm)	21.50	[illegible]	[illegible]	27.60	[illegible]	38.55	[illegible]	[illegible]



MODEL NUMBER	h (mm)	d (mm)	l (mm)
1	0.85	11.90	10.00
2	1.90	14.00	10.00
3	2.90	16.00	10.00
4	4.00	18.20	10.00
5	0.85	11.90	25.00
6	1.90	14.00	25.00
7	2.90	16.20	25.00
8	4.00	18.20	25.00

Fig. 1 Models for heat transfer measurements



SYMBOL	$\frac{h}{L} Re_L{}^{1/2}$	Re_L	M_s	M_f
○	6.0	2.30×10^4	8.65	2.50
□	8.0	4.09×10^4	7.70	2.30
△	10.0	6.40×10^4	7.15	2.15
◇	20.0	2.56×10^5	5.20	1.85

Fig. 2 $q/q_{f.p.}$ as a function of $\Delta x/h$ for Model 1

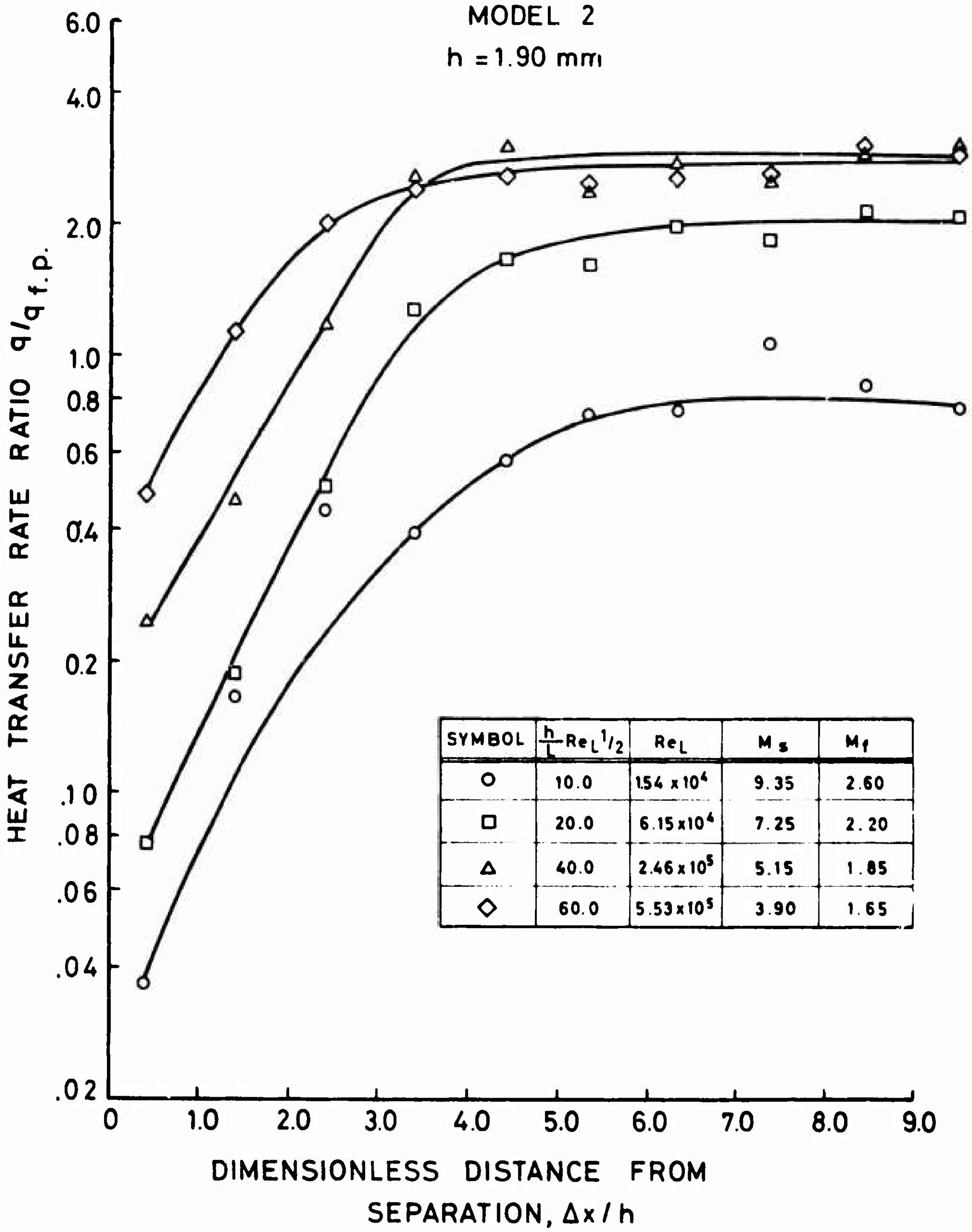


Fig. 3 $q/q_{f.p.}$ as a function of $\Delta x/h$ for Model 2

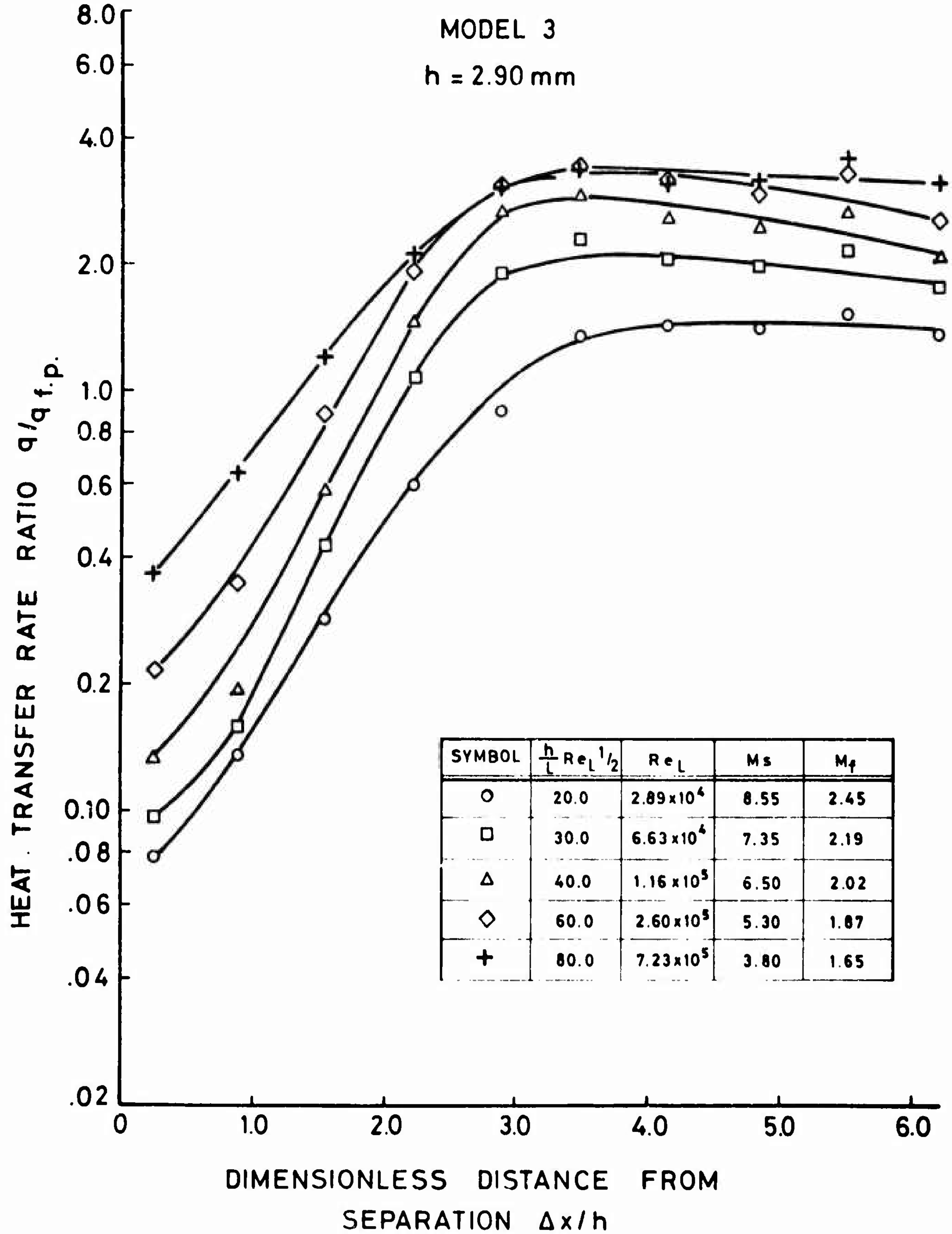
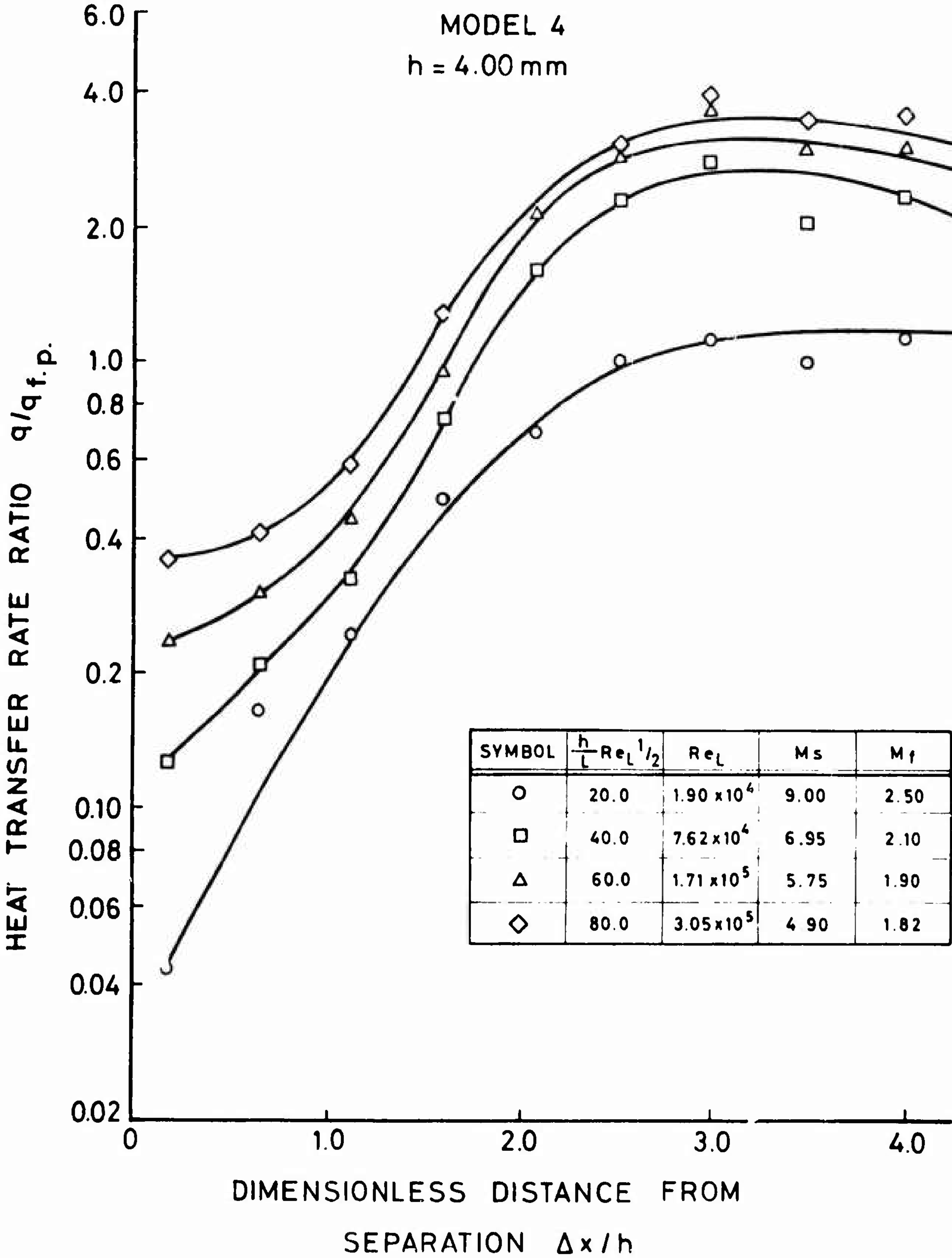
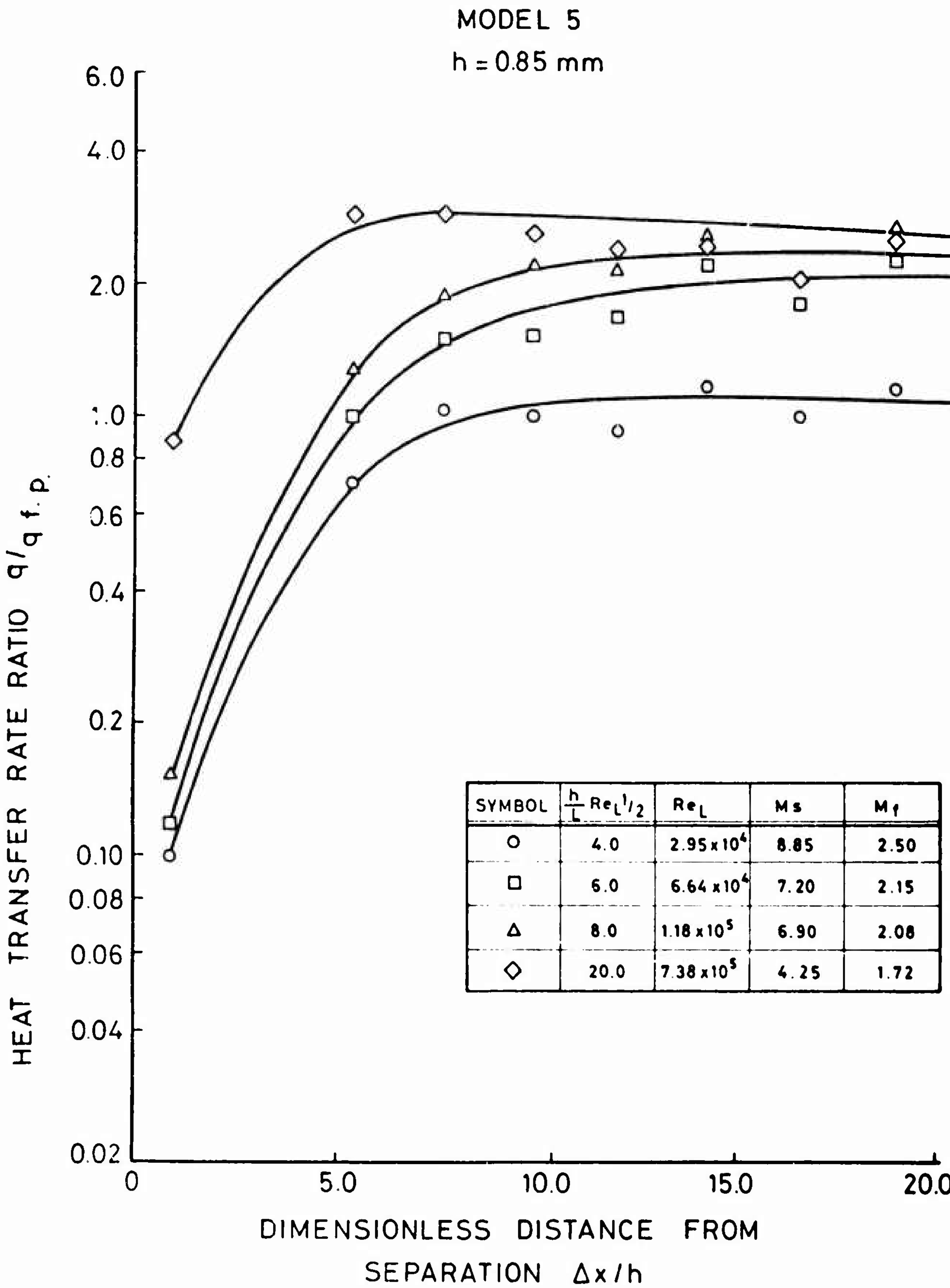


Fig. 4 $q/q_{f.p.}$ as a function of $\Delta x/h$ for Model 3



SYMBOL	$\frac{h}{L} Re_L^{1/2}$	Re_L	M_s	M_f
○	20.0	1.90×10^4	9.00	2.50
□	40.0	7.62×10^4	6.95	2.10
△	60.0	1.71×10^5	5.75	1.90
◇	80.0	3.05×10^5	4.90	1.82

Fig. 5 $q/q_{f.p}$ as a function of $\Delta x/h$ for Model 4



SYMBOL	$\frac{h}{L} Re_L^{1/2}$	Re_L	Ms	M_f
○	4.0	2.95×10^4	8.85	2.50
□	6.0	6.64×10^4	7.20	2.15
△	8.0	1.18×10^5	6.90	2.08
◇	20.0	7.38×10^5	4.25	1.72

Fig. 6 $q/q_{f.p.}$ as a function of $\Delta x/h$ for Model 5

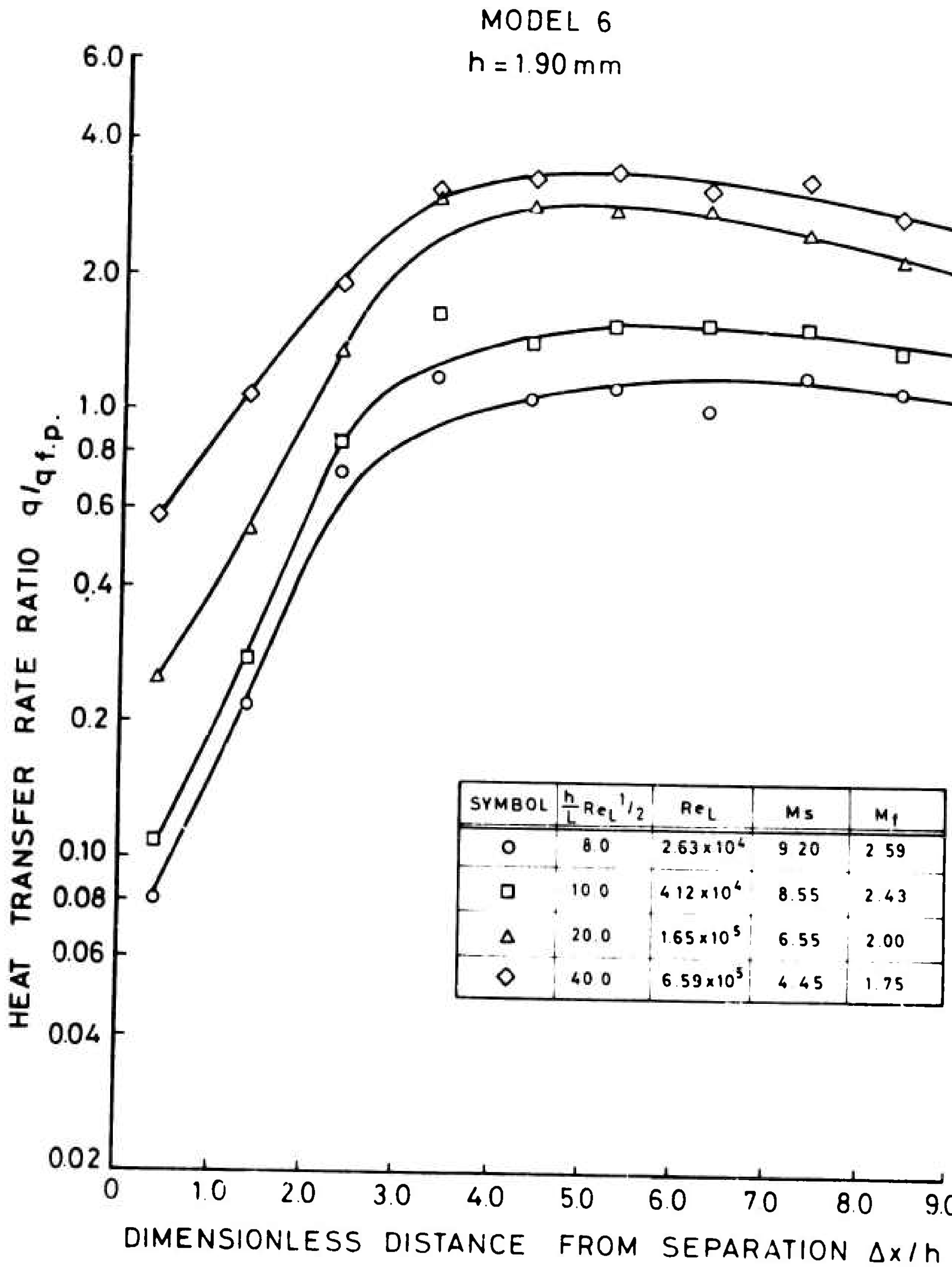

MODEL 6
h = 1.90 mm
HEAT TRANSFER RATE RATIO q/q f.p.
6.0
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0.10
0.08
0.06
0.04
0.02
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
DIMENSIONLESS DISTANCE FROM SEPARATION Δx/h
SYMBOL | h/L Re_L^1/2 | Re_L | Ms | M_f
○ | 8.0 | 2.63 x 10^4 | 9.20 | 2.59
□ | 10.0 | 4.12 x 10^4 | 8.55 | 2.43
△ | 20.0 | 1.65 x 10^5 | 6.55 | 2.00
◇ | 40.0 | 6.59 x 10^5 | 4.45 | 1.75

Fig. 7

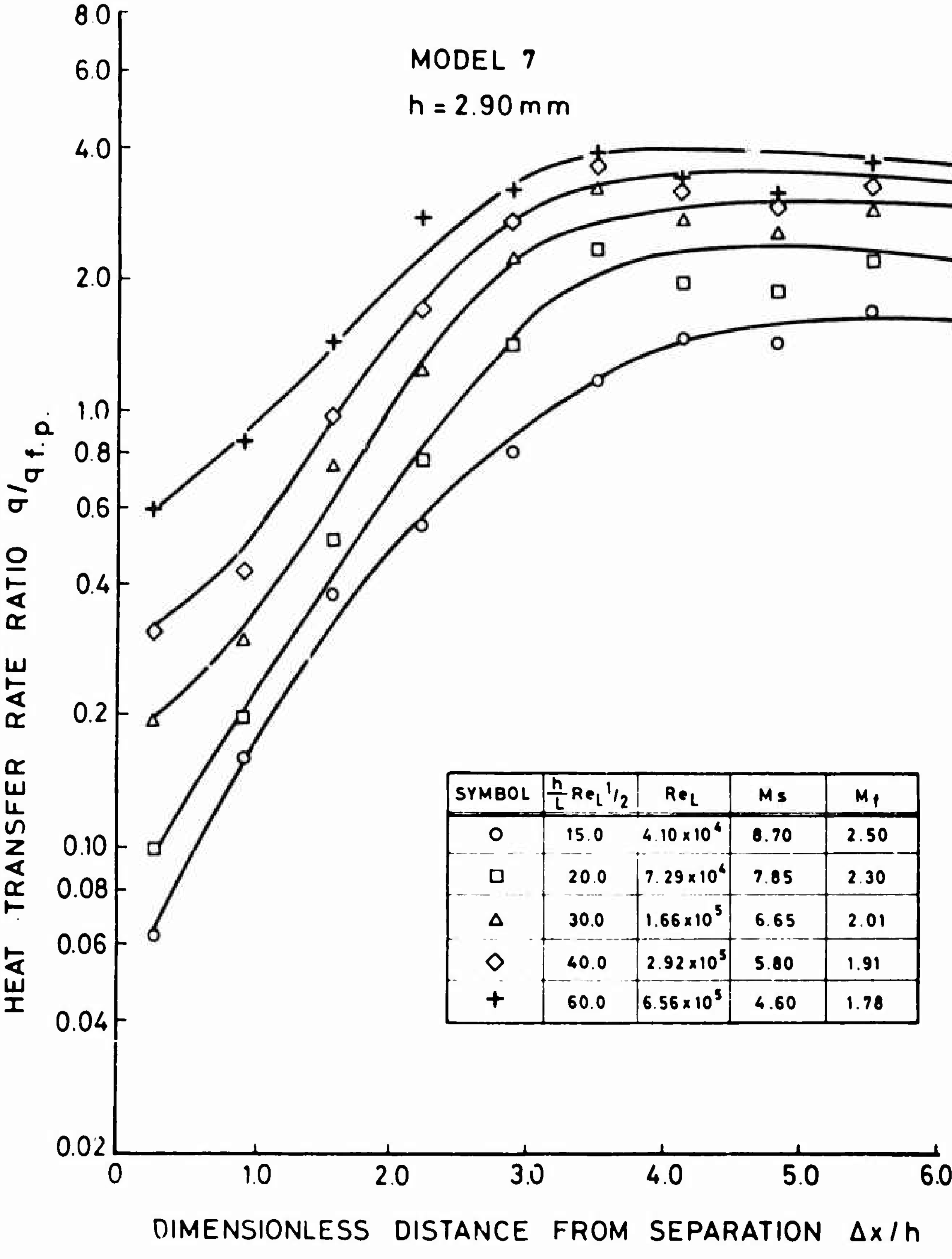


Fig. [illegible] $q/q_{f.p.}$ as a function of $\Delta x/h$ for Model 7

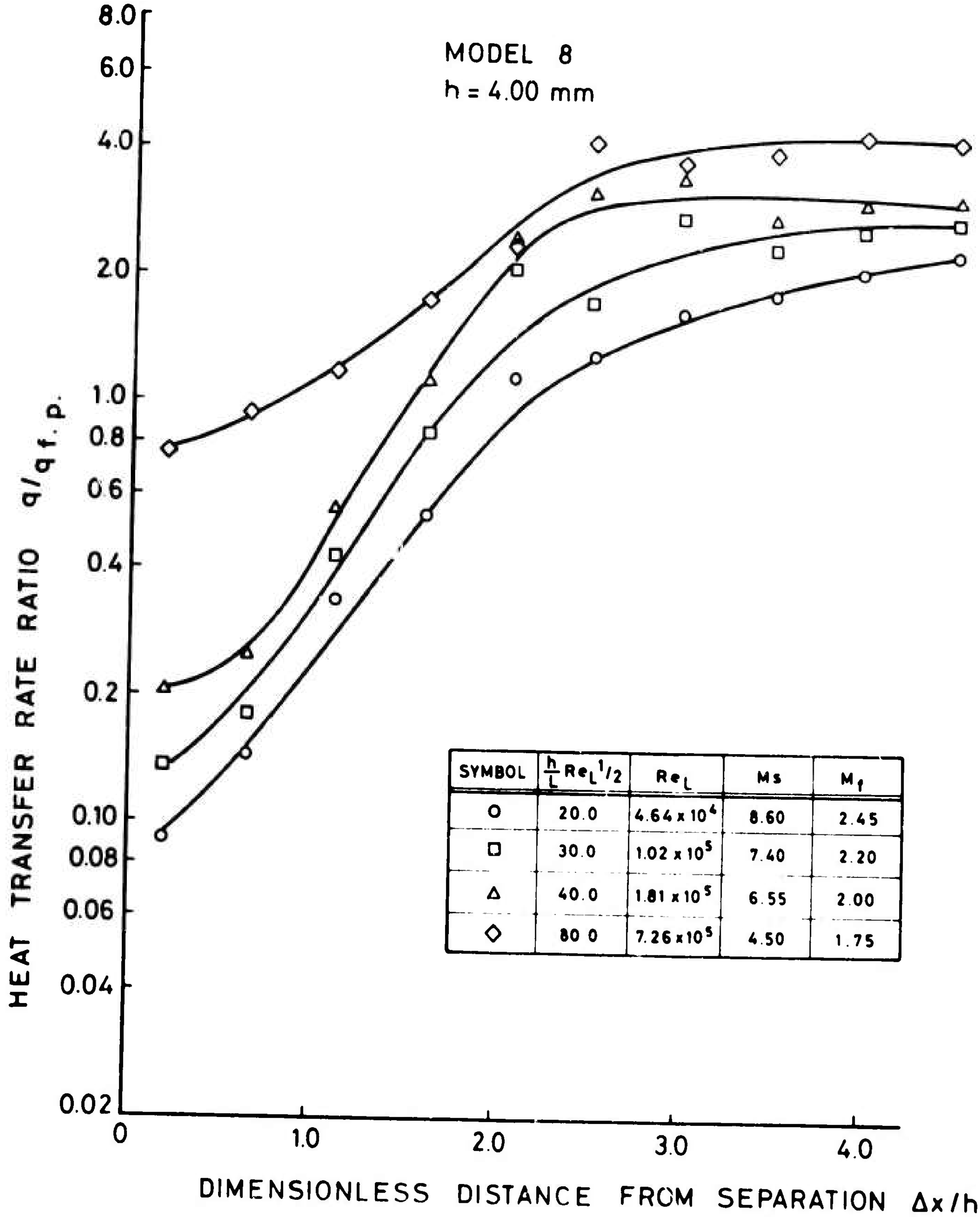


Fig. 9 $q/q_{f.p.}$ as a function of $\Delta x/h$ for Model 8

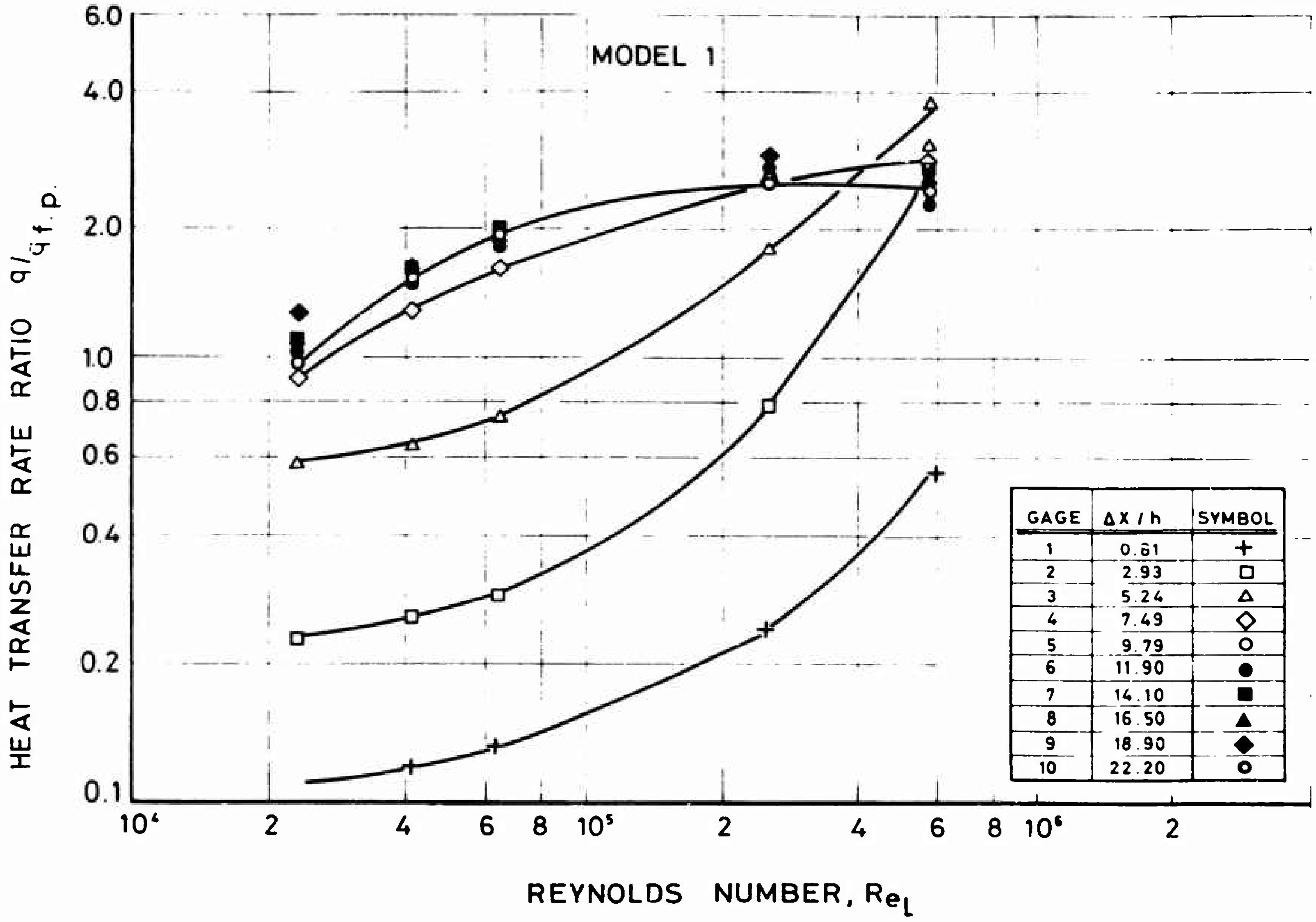


Fig. 10 $q/q_{f.p.}$ as a function of Re_L for Model 1

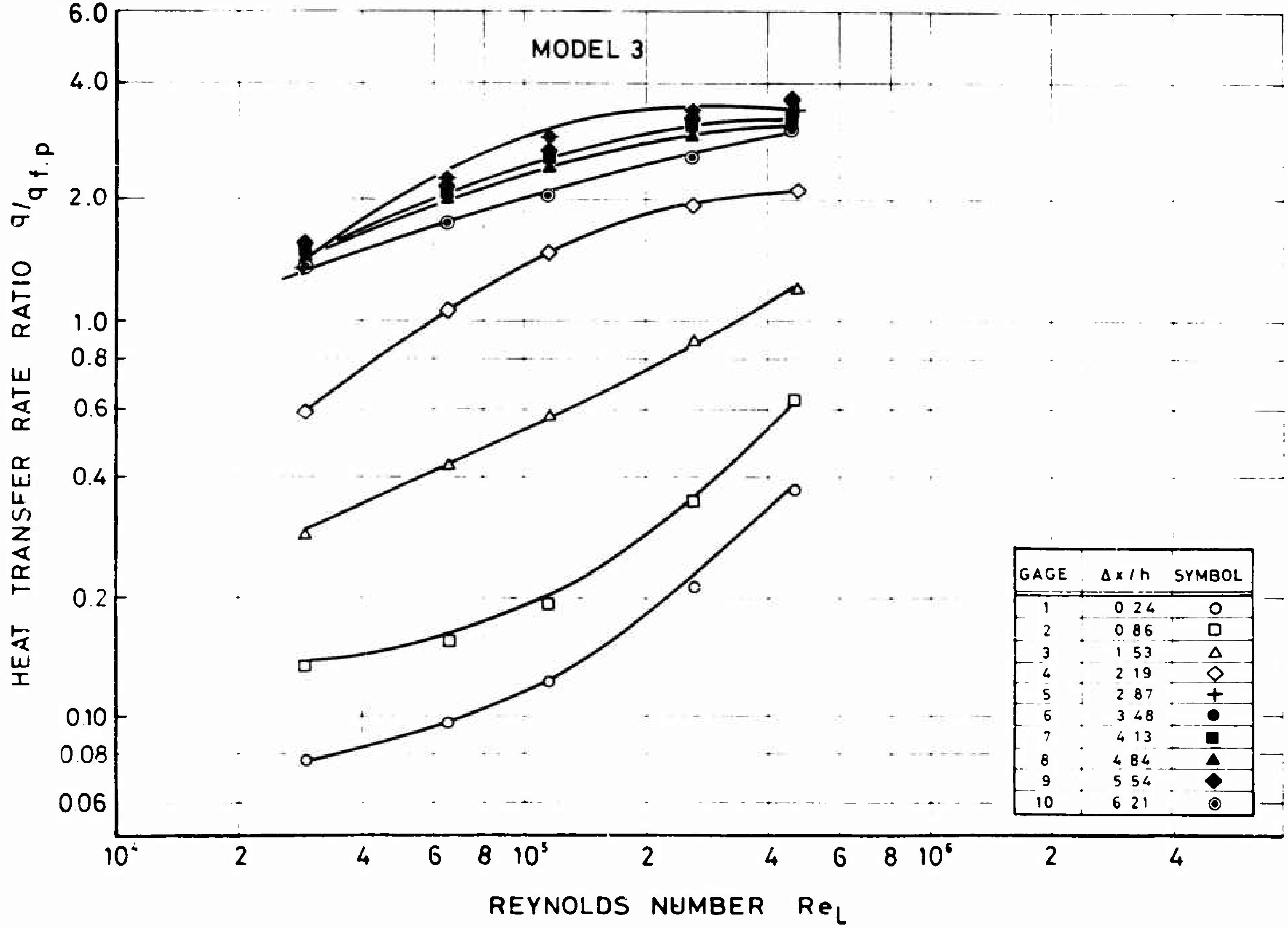


Fig 11 $q/q_{f.p.}$ as a function of Re_L for Model 3

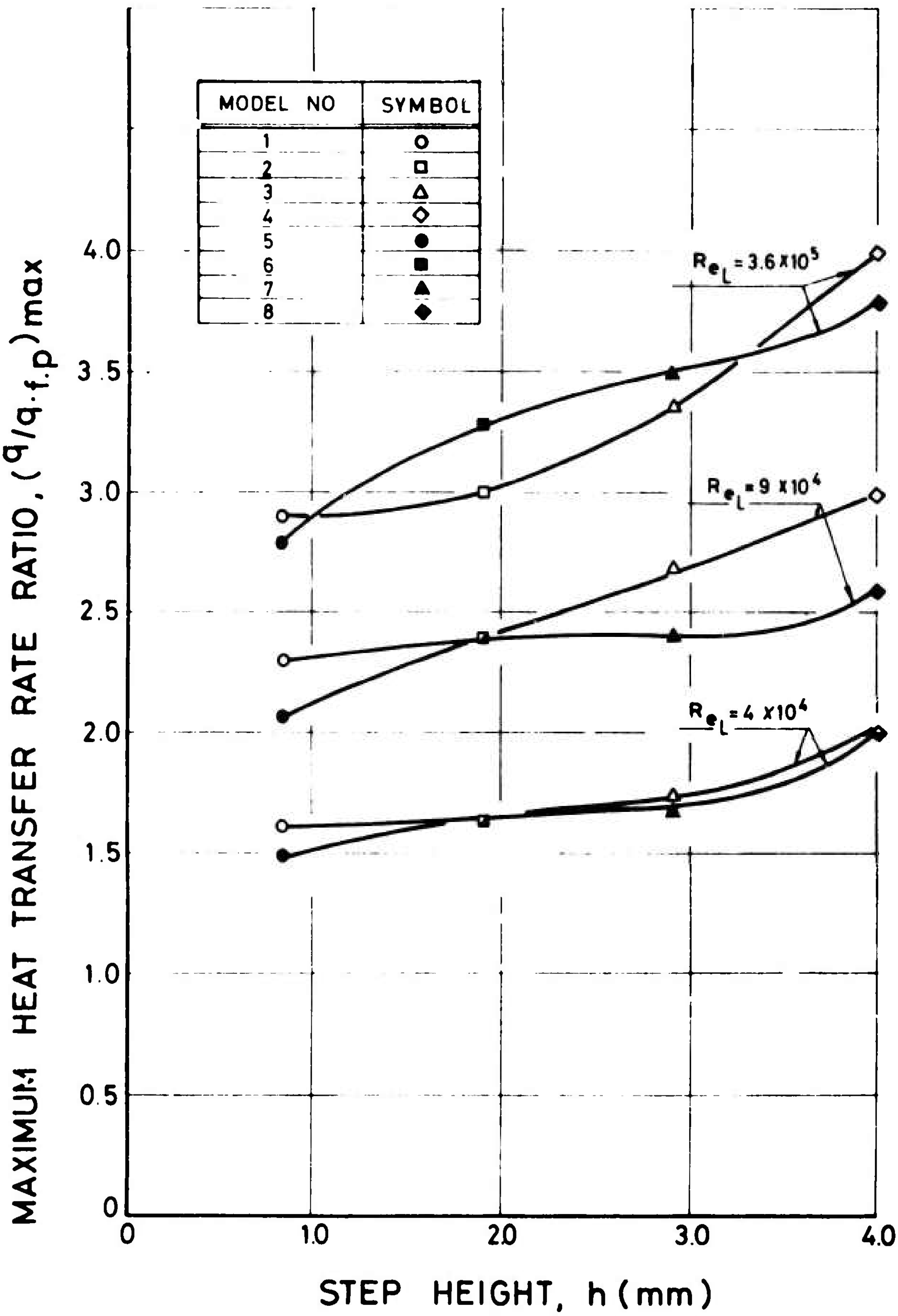


Fig. 12 $(q/q_{f.p.})_{max}$ as a function of h

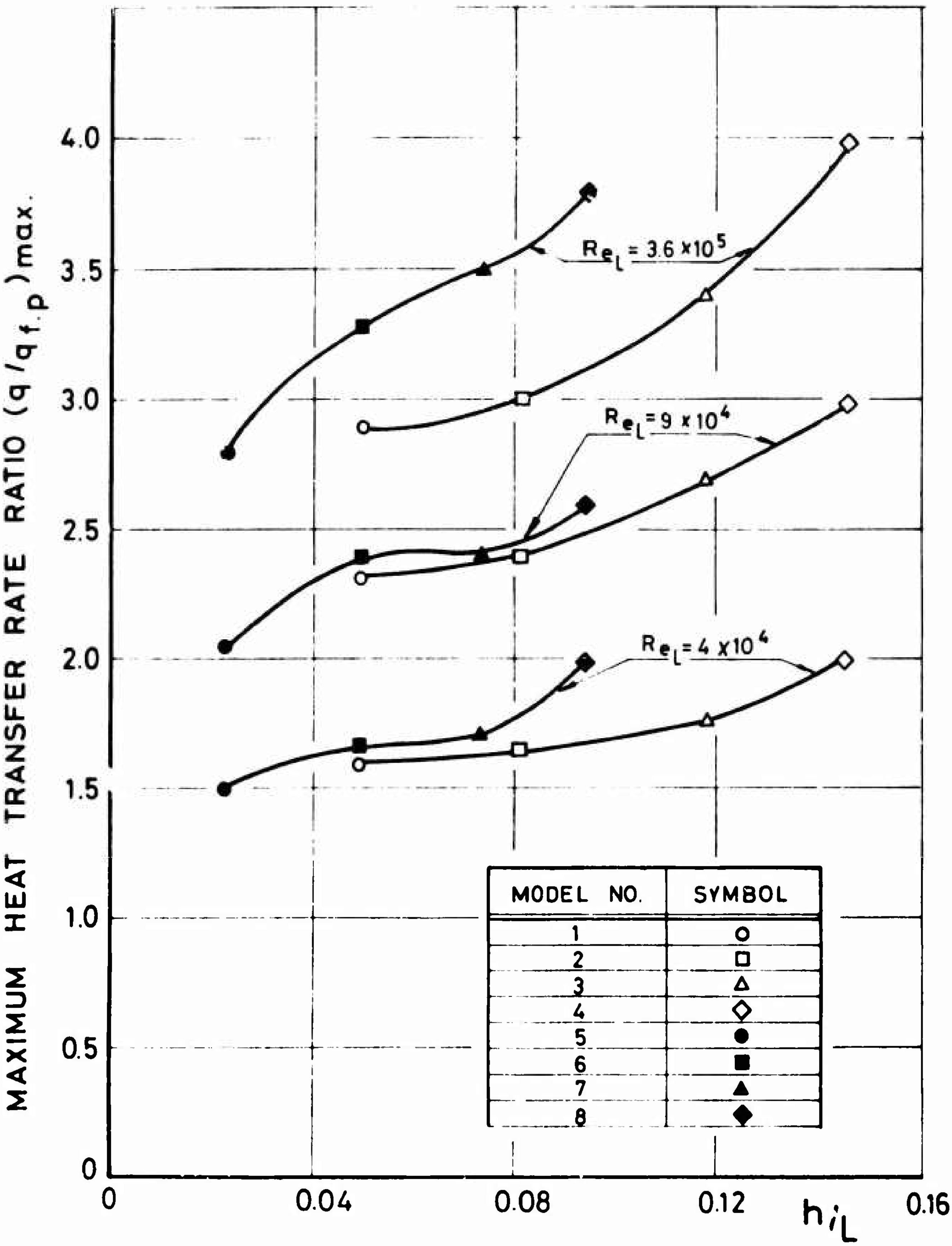


Fig. 13 $(q/q_{f.p.})_{max}$ as a function of h/L

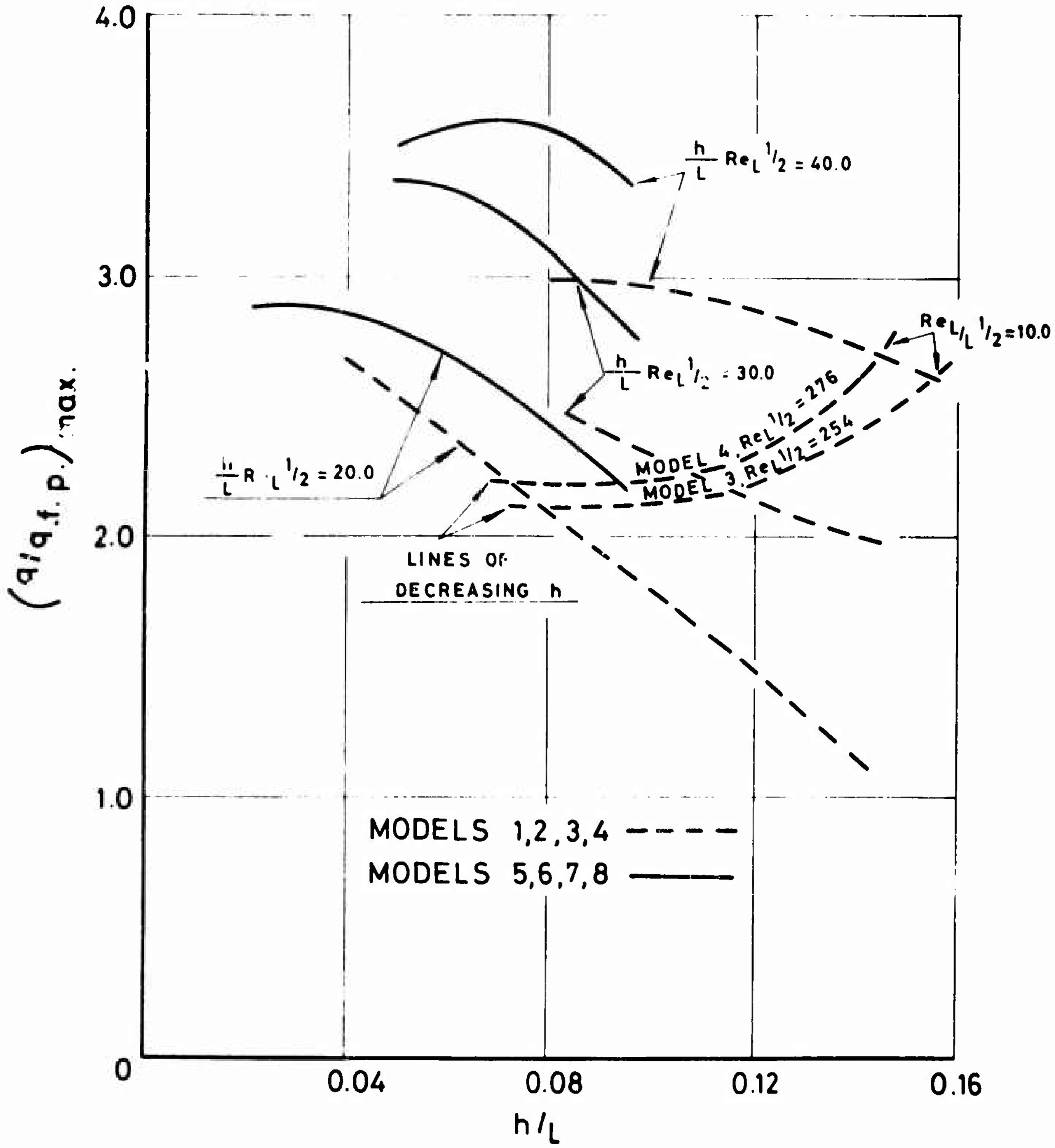


Fig. 14 $(q/q_{f.p.})_{max}$ as a function of h/L

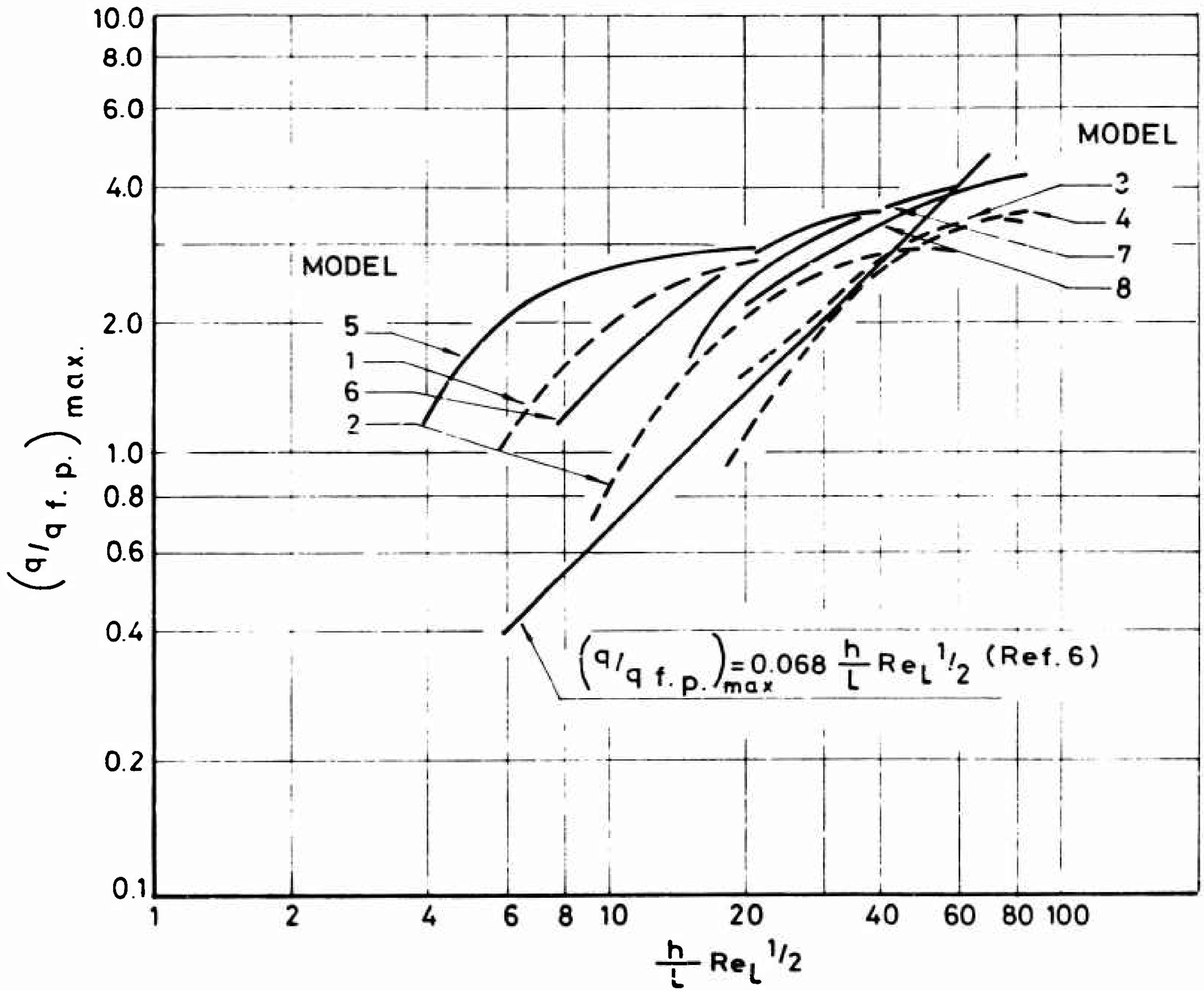


Fig. 15 $(q/q_{f.p.})_{max}$ as a function of $h/L\ Re_L^{1/2}$

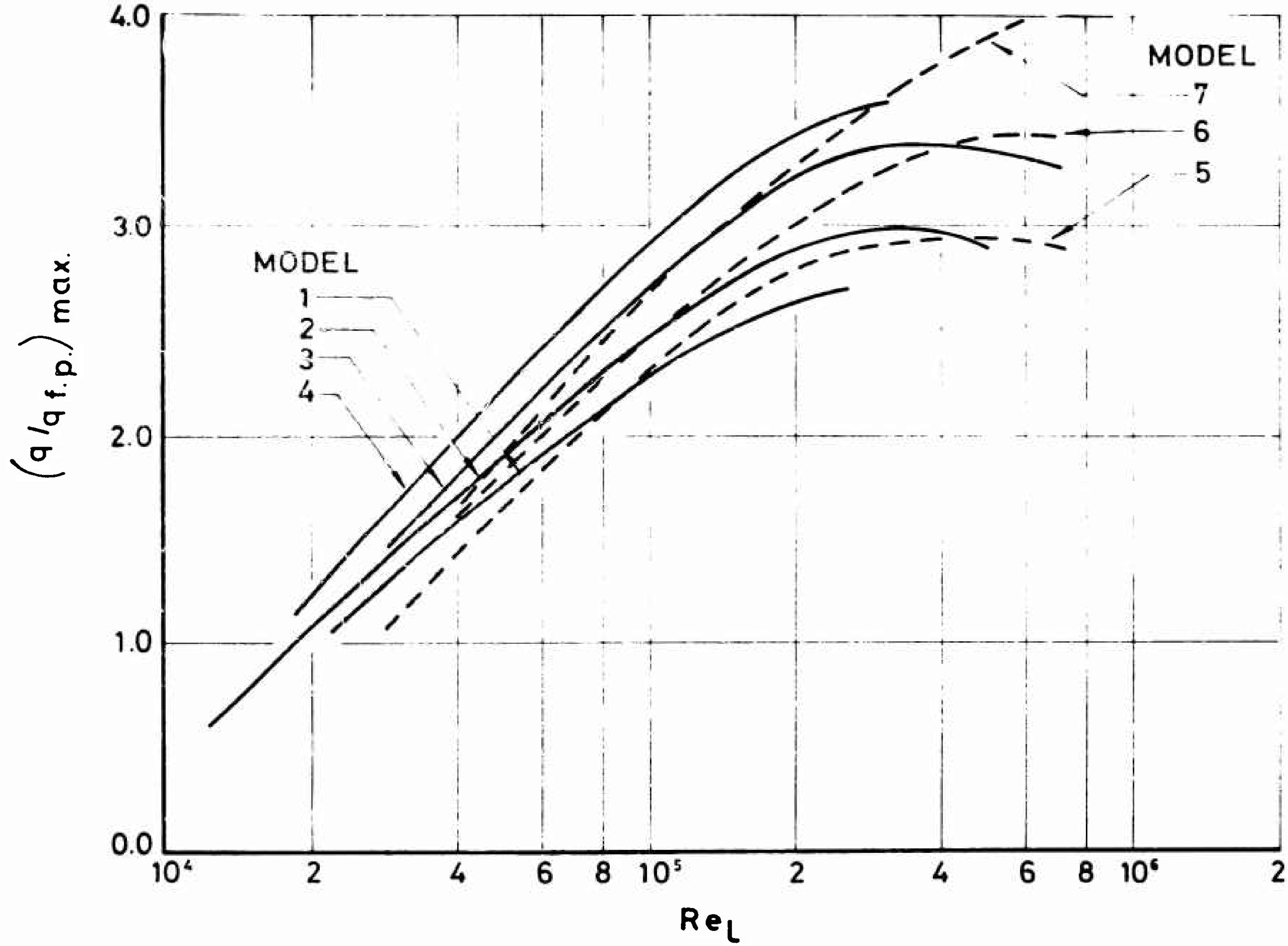


Fig. 16 $(q/q_{f.p.})_{max}$ as a function of Re_L

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2 8

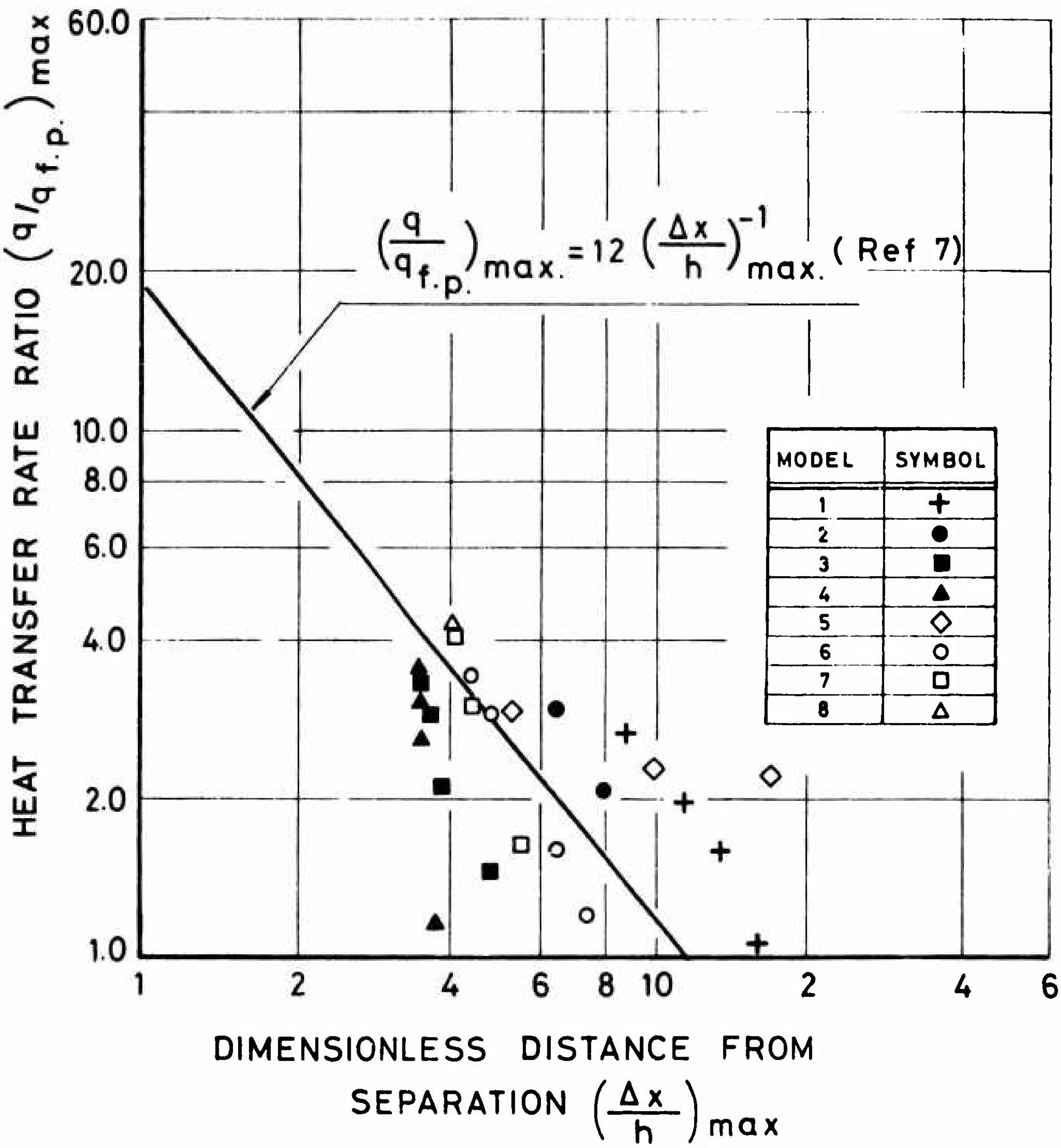

Fig. 17 Maximum heat transfer rate at reattachment as a function of $(\Delta x/h)_{max}$